

MAGNETRON DIRECTIONAL AMPLIFIER SPACE SOLAR POWER BEAMER CONCEPT DESIGN

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Abstract: Current NASA studies of Space Solar Power Systems for delivery from GEO of electric power at 5.8 GHz envision use of a 500m diameter phased array transmitting of order 2 GW to yield 1.2 GWe output to the electric grid from Earth based rectenna arrays. Phase injection-locked magnetron directional amplifiers (MDA) are one approach for the DC to RF converters on the beamer. This approach is based on earlier work by Bill Brown. The key element of the system is the proposed 5 kW output 85.5% efficient, 6 kV MDA with pyrolytic graphite thermal radiator operating at 350 C. Slotted waveguide transmitting antennas are also proposed and their low-cost manufacture and multipacting breakdown margins under 25 kW/m² power flux density in the center of the 10 dB Gaussian tapered aperture are discussed. An average specific areal mass density goal of 35 kg/m² is proposed. EMC issues regarding the close-in carrier noise and harmonic levels are discussed. Grating lobe level maintenance requirements are discussed in regards to the few arc minutes allowed tilt of the entire array, slightly larger arc minute tilts of the individual 4 m subarrays, and maximum allowed random failures of about 2% of the subarrays.

I. INTRODUCTION

Recent studies by NASA of Space (Based) Solar Power [1] have rekindled interest in the design of powerful phased arrays on solar collection satellites at GEO, beaming to Earth based rectenna arrays. At the heart of such a system are the devices for converting the DC power from the solar arrays into coherent RF power for forming the beam to the rectennas.

The power conversion efficiency of the devices is key to the overall link efficiency, and also greatly impacts the spacecraft mass based on the mass of the thermal radiator required to radiate the waste heat into space. The lifetime of the converter is a function of the operating temperature of the radiators. Also, the associated architecture of the microwave power beamer is intimately tied to the

support infrastructure for the type of DC to RF conversion device.

DC-RF conversion devices that are being considered range from solid state power amplifiers (SSPAs), through MDAs to Klystrons. The solid state devices require low voltages around 80 Volts, whereas the Klystrons require of order 50 kV. The solid state junction temperatures must be maintained probably below 250 C for long life even if GaN or lower if SiC and much lower, of order 120C if Si or GaAs devices. 20 to 40 year, utility like lifetimes are desired for SSPs. The temperature of the Klystron collector, where the majority of the waste heat is deposited, may approach 500C, but the magnets and body must be maintained at much lower temperature.

The MDAs may operate their anode passive radiating surfaces at 350C, given

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the current availability of new high-temperature permanent magnet materials. Lower operating voltages were desired, but the conversion efficiencies suffer at lower than 6 kV.

There is a system trade-off concerning the device operating voltages, having to do with the mass of copper or aluminum required to handle the conductor current levels required in the distribution system for low voltage devices.

In order to keep the DC power conductor $I^2\text{-squared-R}$ losses at a minimum, large diameter wire sizes are required, thus more mass. Since the current, I , is proportional to the supply voltage, V , for a given load impedance, the higher supply voltage yields a lower mass distribution system. Lower DC power distribution mass can be achieved by use of lighter mass material, such as aluminum instead of copper, but the conductor distribution loss is also a function of the conductor material conductivity. The actual ratio is a function also of the conductor operating temperature. Generally, aluminum conductors wins out for minimum mass for a given operating temperature and power loss, on terrestrial wired power transmission circuits.

In space, the general means for removing waste heat is with IR-radiation. The quantity of heat radiated is proportional to the area and thus mass of the radiating surface. Another factor is the emissivity of the surface. The power radiated is also proportional to the fourth power of the temperature difference between the thermal radiator and the space background temperature. This latter factor is significant in that it determines the thermal radiator mass, thus driving the DC-RF converters to run at high temperatures. The converse of that desire, which is important for electronic equipment is that the lifetime is usually inversely related to operating temperature. Thus there is a system trade among lifetime, operating temperature and operating voltage.

To add to the overall system considerations is the view factor to space or field-of-view, FOV. If the IR-radiating surface cannot see a goodly portion of cool, deep space, then its efficiency and lifetime is compromised, it runs hotter. Therefore, the layout of the DC converters in the SSP phased array must be such as to see as much as possible of free space (no Earth, no nearby structure, no collection of power feed lines, etc. The very nature of the RF power transmitting phased array is such that its planar configuration with slotted waveguide radiators facing Earth on one side, leaves only the reverse side for exposing the DC-RF converters waste heat radiators.

II. THE ARCHITECTURE OF THE POWER TRANSMITTING PHASED ARRAY

The SSP WPT system consists of a microwave power transmitting phased array in GEO, beaming power to an Earth based rectenna.

At the rectenna, near its center will be a pilot signal transmitter sending a coded beam to the phased array. The pilot beam is for safety reasons and phase information transfer to the GEO array.

The pilot signal promotes power beam safety by providing an interruptible phase reference for the focusing of the power beam. If the pilot signal is not present, the power beam will be randomly phased and the power flux density will decrease by the ratio of the square of the number of individual phased array elements in the array.

The GEO based phased array is composed of an ordered collection of RF-power transmitting elements. Each element consists of individual phase controlled DC to RF converters, all operating at the same frequency, whose outputs feed a planar transmitting antenna. The antennas are configured to

tile the plane of the array aperture. A filled aperture is required to prevent grating lobes and to achieve high beam coupling efficiency with the rectenna. The array elements form a near circular outline, planar aperture that is about 500 m diameter.

The aperture amplitude distribution must be tapered to put most of the transmitted power into a main beam and little into sidelobes. In fact, control of the sidelobes and grating lobes is one of the system electromagnetic compatibility (EMC) requirements. Thus, the transmitting array architecture must provide for a peak of RF power density in the center of the aperture, with a smooth taper or quantized approximation thereto of reduced power density at the edges of the array. The taper is typically Gaussian, with about a -10dB taper, meaning the edge power density is 1/10th that in the center.

To form the power beam, each array element has its RF phase controlled by a retrodirective phase control system. A common frequency reference signal is distributed to all the array elements by a central master oscillator, over a path length compensated distribution system of fiber optic links. At each array element, a diplexed receiver compares the received RF phase of the pilot signal to the distributed reference signal phase and then uses the conjugate of any phase difference to apply to the transmitted power signal. This retrodirective phase control assures that the power beam is focused on the rectenna even though the GEO array may be undergoing mechanical displacements due to structural forces caused by tides, thermal transients or spacecraft attitude control motions.

Based on calculations by Dickey Arndt, Jim Carl and Phong No of the Johnson Space Center, the mechanical pointing of the phased array must be limited to less than an arc minute error, in order to prevent requiring large phase steering of the power beam, as the large area antenna

elements will result in grating lobes being radiated. Grating lobes are replicas of the main beam that are generally suppressed by the array pattern if the beam is not phase scanned very far off boresight (the perpendicular direction from the face of the array). In addition, the local-tilting of the individual phased array antenna elements within the global-plane of the array must also be restricted to on the order of less than 10 arc minutes, to prevent raising the grating lobes beyond acceptable levels by 4 m square subarrays.

Control of the sidelobe and grating lobe levels, along with the close-in carrier noise and harmonics levels, discussed below and conceptually shown in Fig. 1, is a function of how many SSP spacecraft are in view of a spot on the Earth's surface. These random phased extraneous signals will be additive in the power sense, thus for example, 100 spacecraft in view could increase the harmonic level by a factor of 100 or 20 dB. For this reason, the architecture of the WPT system must allow for filters to internally reflect or to absorb unwanted signals.

If the SSP units are to operate under ITU and FCC regulations, there must be electromagnetic filters to keep extraneous signals at the edges of the power beaming frequency band allocation below prescribed levels. Also, in the DC to RF conversion process, harmonics of the fundamental RF carrier frequency are generated. These too must be maintained below acceptable levels. Sharply tuned, electromagnetic resonant structures in such filters must not arc over or breakdown while carrying the high RF power signal.

Multipacting is an insidious form of RF breakdown[2,3] that only occurs under the very high vacuum environment conditions, such as at GEO. At certain electromagnetic voltage levels, there are combinations of the RF wavelength and the dimensions of wave guiding structures that can lead to supporting

multiple impacts of secondary electrons across RF structures, leading to a cascade of electrons producing a conducting plasma or short circuit across the RF structures. Such structural configurations can be single surface as well as the canonical parallel plate electrode pair. For the SSP WPT system, the rectangular waveguide top and bottom walls are the electrodes.

To guard against multipacting, the designer must use multiple parallel low power waveguides, employ lower power level DC to RF converters, fill the waveguides or resonators with solid dielectric (heavy) or pressurize the waveguides (another heavy solution and difficult to maintain for 40 years), or change dimensions if possible. Arcs can be extinguished by turning off the RF power. If not extinguished, the arc will travel back to the power source and hang there leading to a thermal hot spot that will generally result in destruction of the DC-RF converter device.

Neither detailed multipacting designs for the various RF EMC filters nor verification high-vacuum testing has yet been accomplished for SSP.

In addition to filters for EMC, there must be provisions for maintenance of the transmitting array elements in order to repair or replace failed elements at some level of threshold of the number of failed elements at any given time. Failures may happen due to aging or meteor strikes or orbital debris collisions.

Summarizing the WPT array architecture requirements, we need a design of an efficient, light-weight, low-cost, 40 year lifetime, 500 m diameter, filled and tapered aperture, retrodirective phased array, capable of handling multiple GW, with waveguides and RF filters for suppressing harmonics and close in carrier noise that are free of multipacting breakdown. The array must be maintained accurately pointed toward an Earth based rectenna, supported by a structure that does not tilt the elements too

far off plane with a configuration that permits maintenance access while not blocking too much of the view to cool space for thermal reasons.

III. THE MAGNETRON DIRECTIONAL AMPLIFIER

The heart of the MDA SSP architecture rests in the DC to RF converter. William C Brown (1916-1999), the father of modern wireless power transmission by microwaves, developed the magnetron directional amplifier for Solar Power Satellites (SPS) during the 1975-1999 era [4,5], based on a suggestion by this author [6], to phase injection lock the microwave oven cooker tube magnetron oscillator. The magnetron is a one port output power-oscillator, and to couple in a phase locking signal it is necessary to use a circulator or paired magic-T waveguide circuit to introduce the low-power level locking signal and separate it from the high power output signal.

The MDA consists of a phase injection locked magnetron oscillator tube with two key modifications designed by Bill. The tube has its permanent magnet augmented with a magnetic bias coil for increasing or decreasing the magnetron oscillator magnetic field, depending on the direction of current flow in the coil. This allows the magnetron output power level to be controlled.

The second modification was to add a variable-position tuning slug in the output waveguide. This allowed the rest frequency of the magnetron to be tuned, by varying the load impedance.

By placing the control of the magnetic bias field and the reactance tuning in independent control loops, Bill was able to create a potentially low-cost, efficient, high-power DC-RF converter with independent control of frequency, phase and amplitude. Bill's work was further amplified by the August 1999 Thesis: *Characterization and Optimization of the Magnetron Directional Amplifier*, by

Mike Hatfield while at the University of Alaska Fairbanks[7].

Nevertheless, the detailed design of an application specific integrated circuit (ASIC) and the companion monolithic microwave integrated circuit (MMIC) for performing the MDA control functions has not been done.

In the 500 m diameter phased array, the frequency and phase reference comes from the phased array retrodirective system electronics. The amplitude reference is based on the position of the element in the array aperture taper.

The GEO, space-based version of the MDA will use magnetrons specially manufactured for that environment. Such detail design has not been done, but we estimate that a 5 kW output unit, operating at 5.8 GHz could be made with about 85.5% conversion efficiency with a supply voltage of 6 kV. The tube with magnet coil, reactance tuner, circulator and 44 cm. diameter, 350 degree C pyrolytic graphite tapered circular disk waste heat thermal radiator would mass about 1 kg. To assure a clean spectrum and long life for the magnetron, it would be operated with filament off after start up[8]. The start up would require about 5 seconds with 70 W of filament power. Approximately 400,000 MDAs would be needed for a 2 GW radiated power array.

IV. SLOTTED WAVEGUIDE ANTENNA AND RF POWER DISTRIBUTION

The power output from the MDAs, after the required EMC filtering, must be spread uniformly across a portion of the array aperture by use of an antenna designed to radiate the power signal. We are looking at slotted waveguide antennas for that function. A conceptual design architecture is shown in Figure 2.

A waveguide corporate feed distribution system will deliver power to parallel stacks of slotted waveguides in a resonant standing wave configuration. In the

center of the array where the power density is highest ($\sim 25 \text{ kW/m}^2$), each slot ($\sim 1100 \text{ slots/m}^2$) must radiate about 23W.

Bill Brown also worked out a technique for low-cost mass production [9] of the large quantity of slotted waveguide antennas per SSP. Figure 3 shows how the top and bottom planes of the antenna could be generated from spotwelding folded and punched sheet aluminum foil. The tooling for such a system is yet to be produced. (Tooling availability could make beamed power to airship platforms more affordable also, for those applications using slotted waveguide transmitting phased arrays.)

As currently envisioned, the SSP central antenna elements will be made in 4m X 4m squares. Thus a square array of 9 X 9 MDAs must have their RF outputs spread across the back face of the antenna. At the edge of the array, only 9 MDAs will be needed per 4m X 4m antenna, yielding a -9.54 dB taper across the array aperture.

Thus, the approach to producing the required beam-coupling efficiency-taper is to use fixed power output MDAs (5 kW) driving fixed slot antennas, but through power dividers whose division ratios change as a function of radius in the aperture such that the power density is a Gaussian taper approximation. The design of the optimum power splitting waveguides has not yet been done. A goal is to minimize the number of different waveguide dividers in order to reduce the number of spares required to be stocked for maintenance purposes.

A central, redundant pair of antenna elements will need to be diplexed, that is, supplied with frequency separating filters to allow the pilot tone to be separated from the power beam signal for the retrodirective function. This will cause some additional insertion loss to those antenna elements, but the same phase information can be used for all the other antenna elements in a mechanical

subarray. Those other elements need not suffer the increased loss, and as they are the majority, the effect on the overall array efficiency is small.

The thermal waste heat must be principally dumped from the back side of the array, given that the thin walled (0.5 mm) aluminum waveguide in the power splitters and slotted waveguides will not provide significant heat transport by conduction to the front side where the RF radiating slots are located. In fact, multi-layer thermal insulation (MLI) blankets will be required under the magnetron pyrolytic graphite elements in order to reflect the IR-waste heat away from the thermally sensitive electronics involved in the retrodirective phase control function and any other low-temperature (95C) electronics such as instrumentation and controls or narrow-tuned RF filter resonators.

The DC power required by the MDAs must also be distributed across the back of the array in a Gaussian density with radius. The design voltage for the magnetrons is 6 kV, a compromise between higher voltage for lower distribution losses and lower voltage for conversion efficiency. Again, a detailed design has not been done. The regulation of the supply voltage is not critical due to the buck-boost coil design developed by Bill Brown. The amplitude control loop is predicted to accommodate about +/- 5% voltage variation before the efficiency suffers.

V. RECOMMENDATIONS

1. Perform detailed multipacting RF breakdown design and high-vacuum verification testing for suitable EMC filters and waveguide assemblies.
2. Develop the ASIC & MMIC circuits that are needed to permit low cost WPT DC-RF converters using modified microwave oven cooker tubes.

3. Develop the tooling to permit low cost fabrication of 2.45 or 5.8 GHz slotted waveguide antennas from aluminum foil, for power beaming array applications.

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SSP WPT Spatial & Spectral Interfaces

ANSI/IEEE C95.1:
Human Exposure
@5.8 GHz in an
Uncontrolled Environment
< 3.87mW/cm² Averaged
over 30 minutes.
Controlled Environment
<10mW/cm² Averaged
over 6 minutes.

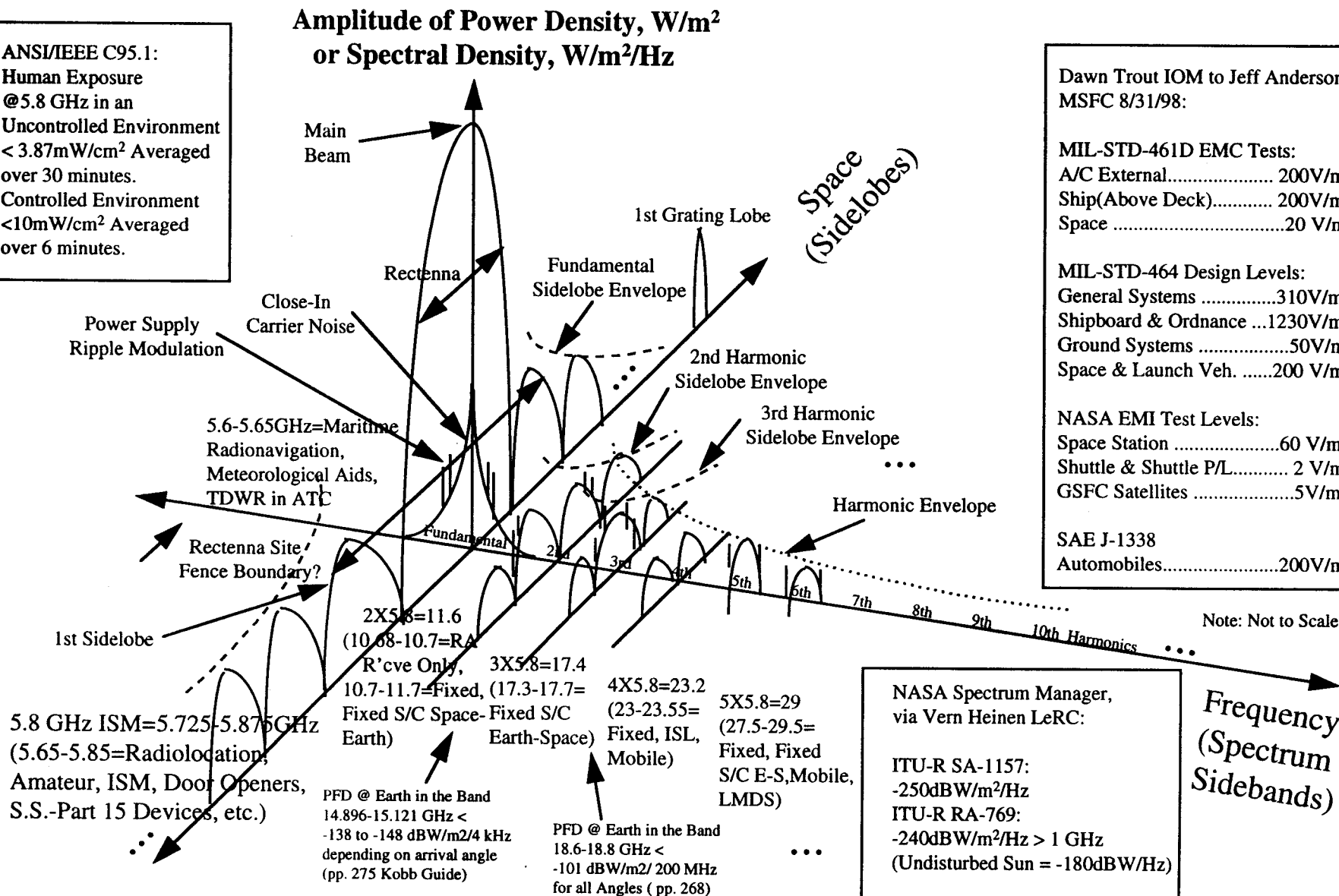
Dawn Trout IOM to Jeff Anderson
MSFC 8/31/98:

MIL-STD-461D EMC Tests:
A/C External..... 200V/m
Ship(Above Deck)..... 200V/m
Space20 V/m

MIL-STD-464 Design Levels:
General Systems310V/m
Shipboard & Ordnance ...1230V/m
Ground Systems50V/m
Space & Launch Veh.200 V/m

NASA EMI Test Levels:
Space Station60 V/m
Shuttle & Shuttle P/L..... 2 V/m
GSFC Satellites5V/m

SAE J-1338
Automobiles.....200V/m



NASA Spectrum Manager,
via Vern Heinen LeRC:

ITU-R SA-1157:
-250dBW/m²/Hz
ITU-R RA-769:
-240dBW/m²/Hz > 1 GHz
(Undisturbed Sun = -180dBW/Hz)

(World Countries= 239)

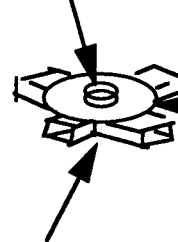
5.8 GHz Magnetron Directional Amplifier (MDA) SSP Subarrays*

by Richard M. Dickinson, JPL

Total "Average" Mass Density ~ 32 kg/m²

Peak Mass Density = Transmitter@ 5.7 kg/m²
Antenna @ 6 kg/m²
Absorptive & Reflective Filters @ 2 kg/m²
HVDC Distribution Lines@0.263 kg/m²
TOTAL Peak Density = 14 kg/m²
Edge Subarray Density = 7.7 kg/m²
Est. PMAD@ 1.5kg/kW ~20kg/m²

5 kW RF out, 85.5% efficient Magnetron, ~1kg,
6 kV, 1A & 70 W, 5s-Starting Filament & Off

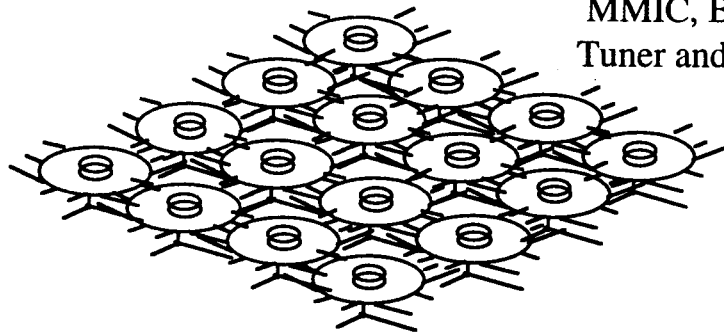


44 cm dia., 350 deg C Pyrolytic
Graphite Radiator Dumping 850W

MLI Blankets
Over 95 deg C
Electronics

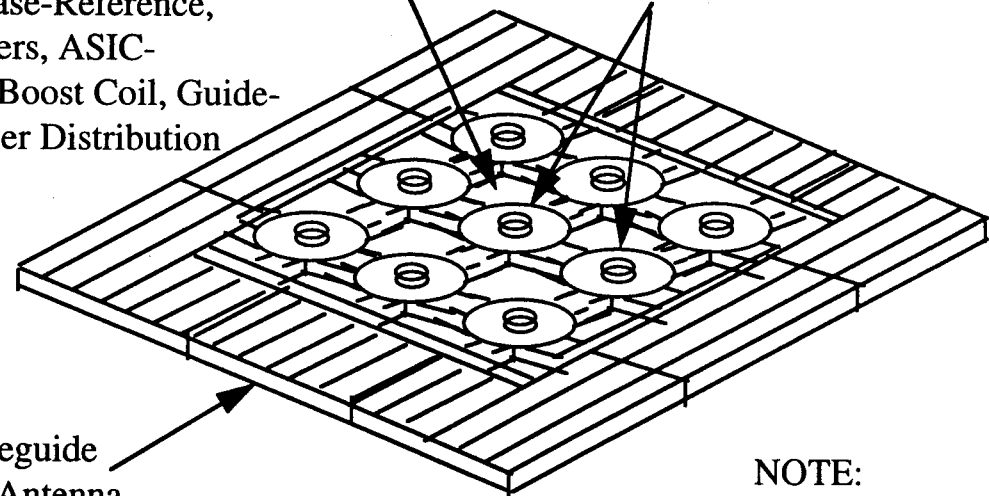
Two Central Devices Diplexed
for Retrodirective Pilot Beam
Receiver Function

Waveguide Phase-Reference,
Circulator, Filters, ASIC-
MMIC, Buck-Boost Coil, Guide-
Tuner and Power Distribution



Portion of 4m X 4m
Central Subarray with
9 X 9 = 81-MDAs
Yielding ~ 25 kW/m² PFD
for 1.2 GWe System

Slotted Waveguide
Transmitting Antenna
~ 6 kg/m², 0.5 mm (.02')
Aluminum (~ 1100slots/m²)
~ 3.2 cm thick (Cross Feeds
+ Radiating Waveguides)



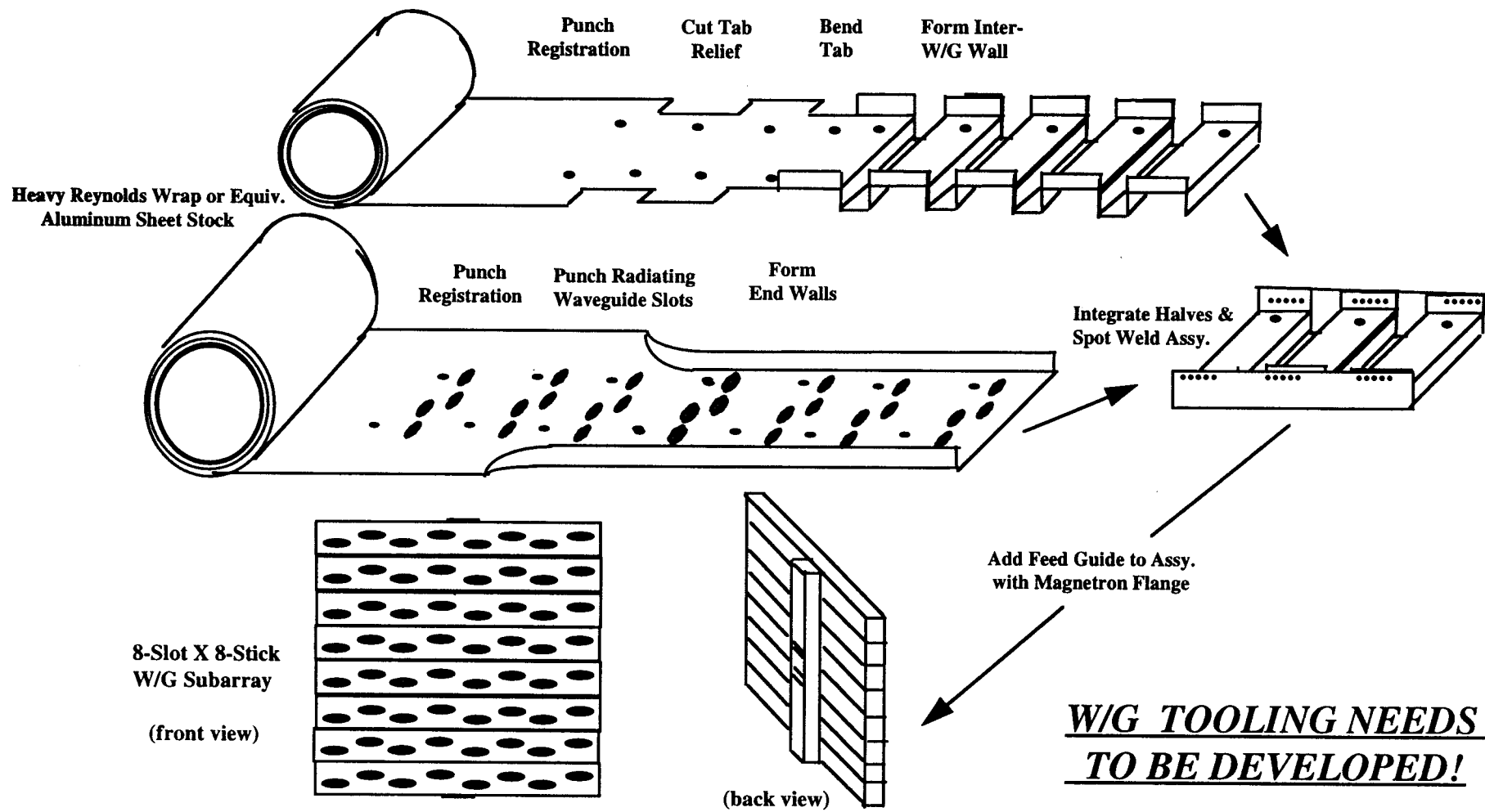
4m X 4m
Edge Subarray
3 X 3 = 9-MDAs
Yielding ~ 2.8 kW/m² PFD
and thus -9.5 dB Aperture Taper

NOTE:
Not To Scale

* Var. of Brown, W. C., "Satellite Power System (SPS) Magnetron Tube Assessment Study, " NASA Contract NAS-8-33157, for MSFC, 7/10/80.

Slotted Waveguide Subarray Low Cost Manufacture

Concept by Bill Brown[1]



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